Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
12 (2008) 839–851
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Wind energy potential of Gökçeada Island in Turkey

N. Eskin[a,*], H. Artar[a], S. Tolun[b]

[a]*Faculty of Mechanical Engineering, İstanbul Technical University, İnönü Cad. No. 87, Gümüşsuyu-Taksim, 34437 İstanbul, Turkey*
[b]*Faculty of Aeronautics and Astronautics, İstanbul Technical University, 34469 Maslak/İstanbul, Turkey*

Received 28 March 2006; accepted 24 May 2006

Abstract

The main objective of the present study is to estimate wind power potential of Gökçeada Island in the Northern Aegean Sea in Turkey using the wind data collected at four different locations. Wind data collected over a period of 3 years at Uğurlu and Çınaraltı stations and a period of 10 years at Aydıncık and National Weather Station. In this regard, wind data collected at 10 and 30 m of height above ground, were extrapolated to 50 m which had been chosen as the wind turbine hub height, using power law. Extrapolated wind data of four stations were represented by Weibull probability density functions to find the wind speed distribution curves. Two Weibull parameters of the wind speed distribution function, shape parameter k (dimensionless) and scale parameter c (m/s) were calculated by the developed Fortran programme on monthly and yearly basis to find the wind profiles. Annual wind speed distributions throughout the Gökçeada Island were also obtained using the calculated Weibull probability density function parameters. The suitability of the distributions is judged by the discrepancies between the observed and calculated values of the monthly average wind speed. The results show the general availability of wind energy potential across Gökçeada Island.

Keywords: Wind energy potential; Wind data; Weibull parameters; Weibull distribution; Turkey

Contents

*Corresponding author. Tel.: +90 212 252 53 54; fax: +90 212 245 07 95.
E-mail address: eskinn@itu.edu.tr (N. Eskin).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2006.05.016

1. Introduction

The main source of energy for some of the Turkish Islands is diesel and heavy fuel oil. Main islands have grid connection such as Gökçeada, Bozcaada. Even though there is an abundance of renewable energy sources, their use is limited. Availability of imported energy supplies and fluctuations in the increasing trend of international energy prices strongly influences island-wide economic development. As the energy demand and consumption increases, limited energy sources create on urgency to find new solution for this energy shortage. Besides that, the environmental impacts of hydrocarbon fuels have led to a major effort in finding other means for energy production; renewable energy system seems to have the potential to alleviate environmental problems. The renewable energy sources are friendlier to the environment compared to fossil fuels, which contribute by far in many environmental problems that the world faces today (greenhouse effect, pollution to atmosphere, soil and water) renewable energy of wind can be an alternative energy solution.

The wind characteristics were extremely important in the field of structural, environmental and mechanical engineering design in the past [1,2]. Today, wind analysis provides remarkable information to researchers and designers that are involved in renewable energy studies. The global wind energy industry has been setting on record for newly installed penetrating capacity since the late 1990s. Technological progress has also dramatically reduced the price of the wind power in favorable locations in such a way that the rate of growth appeared likely to maintain wind's position as one of the world's fastest growing energy sources [3]. Besides that, the wind climate in Turkey induces high winds in many places. Therefore among various renewable energy sources in Turkey wind energy is one of the most promising renewable energy sources [4].

Knowledge of the statistical properties of the wind speed is essential for predicting the energy output of a wind energy conversion system [1,2]. Therefore it is important to verify the method of analysis being used on the measured wind data due to the high variability in space and time. In recent years, some researchers have carried out the evaluation of wind energy potential for different regions by using various probability distribution functions [5,6]. The numerous studies for different locations of the world have shown that the Weibull two-parameter distribution gives favorable fits to the wind speed distributions [7–9].

The aim of this paper is to address the study of the statistical properties of the wind speed and wind potential in Gökçeada by considering four locations in which the data are currently recorded by Istanbul Technical University (ITU), EIE and to verify the adequacy of the Weibull distribution for describing the wind speed data of the considered stations.

Nomenclature

c	Weibull scale parameter (m/s)
E/A	wind energy density (W/m^2)
$f(V)$	Weibull probability density function
$F(V)$	Weibull cumulative density function
k	Weibull shape parameter (–)
n	number of wind speed data (–)
$V(z)$	wind speed at height z (m/s)
$V(z_r)$	wind speed at anemometer height (m/s)
$V_{\mathrm{Max,E}}$	wind speed carrying maximum energy (m/s)
V_{mean}	mean wind speed (m/s)
V_{mp}	most probable wind speed (m/s)
P/A	wind power density (W/m^2)
z	height (m)
z_r	anemometer height (m)
α	power-law exponent (–)
σ	standard deviation (–)

2. Mathematical formulation

There are several continuous mathematical functions, or the so-called probability density functions, that can be used to model the wind speed frequency curve by fitting time-series measured data. In wind power studies, the Weibull and Rayleigh probability density functions are commonly used and widely adopted [10]. Herein the Weibull distribution is used since the Rayleigh distribution is only a subset of it.

The Weibull probability density function is a special case of a generalized two-parameter Gamma distribution. The general form of the Weibull distribution function for wind speed can be characterized by its probability density function $f(V)$ and cumulative distribution function $F(V)$ as follows [11]:

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left(\left(-\frac{V}{c}\right)^{k}\right) \tag{1}$$

and

$$F(V) = 1 - \exp\left(\left(-\frac{V}{c}\right)^{k}\right), \tag{2}$$

where k is the dimensionless Weibull shape parameter and c Weibull scale parameter in the units of wind speed. In order to estimate the two parameters of Weibull distribution, numerous methods have been proposed over the last few years. In this paper, maximum likelihood method is applied to find the parameters as suggested in the following iterative

equations [12]:

$$k = \left(\frac{\sum_{i=1}^{n} V_i^k \ln(V_i)}{\sum_{i=1}^{n} V_i^k} - \frac{\sum_{i=1}^{n} \ln(V_i)}{n} \right)^{-1}, \tag{3}$$

$$c = \left(\frac{1}{n} \sum_{i=1}^{n} V_i^k \right)^{1/k}. \tag{4}$$

In these formulas, "n" represents the number of non-zero wind speeds in the time-series data and V_i is the wind speed in time stage i.

Mean value of wind speed and its standard deviation may be computed as [13]

$$V_{\text{mean}} = c\Gamma\left(1 + \frac{1}{k}\right), \tag{5}$$

$$\sigma = \sqrt{c^2 \left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{2}{k}\right) \right]}, \tag{6}$$

where Γ denotes the gamma function.

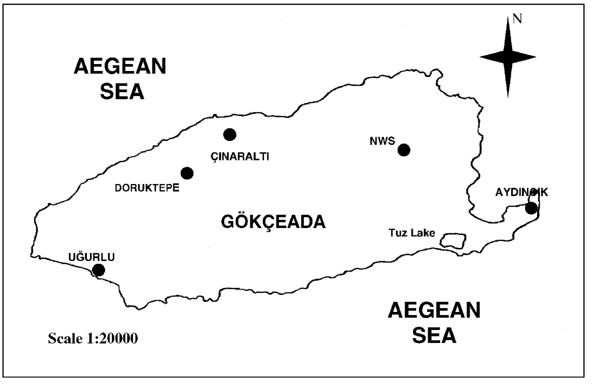

Fig. 1. Map of Gökçeada Island indicating locations of the stations.

Table 1
Wind speed observation stations in Gökçeada Island

Station	Geographical coordinates	Elevation from mean sea level (m)	Years of wind data available	Remarks
Aydıncık	40°08′37″N–26°00′18″E	25	1994–2002	Rural, coastal
Uğurlu	40, 11°N–25, 73°E	35	1991–1994	Rural, coastal, scarcely vegetated
Çınaraltı	40, 20°N–25, 83°E	250	April 1992–1994	Rural, coastal, vegetated
National Weather Station (NWS)	40, 74°N–25, 92°E	71	1979–1989, 1991–1993	Urban, interior

As the scale and shape parameter have been calculated, two meaningful wind speeds for wind energy estimation, the most probable wind speed and the wind speed carrying maximum energy can be easily obtained. The most probable wind speed denotes the most frequent wind speed for a given wind probability distribution and is expressed by

$$V_{\mathrm{mp}} = c\left(k - \frac{1}{k}\right)^{1/k}. \tag{7}$$

Wind speed carrying maximum energy represents wind speed which carries maximum wind energy can be expressed as follows [13]:

$$V_{\mathrm{Max,E}} = c\left(k + \frac{2}{k}\right)^{1/k}. \tag{8}$$

It is well known that the power of the wind that flows at speed V through a blade sweep area A increases as the cubic of its velocity and is given by

$$P(V) = \tfrac{1}{2}\rho A V^3, \tag{9}$$

Table 2
Wind measurement devices and basic properties

Component name	Component model	Sensitivity	Working range
Wind Vane	NRG 200P	1%	360° mechanical rotation
Anemometer	NRG 40	0.1 m/s	1–96 m/s wind speed
Data Logger	NRG Logger 9200 plus	0.0625 Hz (0.0022 m/s)	1–97.4 m/s wind speed (0–127.5 Hz)

Table 3
Aydıncık monthly average wind speeds between the years 1994 and 2002 (at 50 m, in m/s)

Month	Year							
	1994	1996	1997	1998	2000	2001	2002	1994–2002
January	10.58	11.65	10.03	7.07	9.10	9.81	9.11	9.62
February	9.98	11.84	10.39	8.64	9.45	9.08	7.19	9.51
March	10.26	10.86	10.43	11.16	10.60	8.84	9.69	10.26
April	8.64	6.14	8.29	9.70	4.93	7.55	7.65	7.56
May	6.11	7.39	11.59	7.94	6.88	6.40	7.49	7.69
June	7.37	8.07	—	6.95	8.07	6.69	7.48	7.44
July	11.17	9.07	—	—	6.93	7.21	6.53	8.18
August	8.20	8.63	—	—	9.63	9.17	7.60	8.65
September	8.26	7.29	9.91	—	8.77	6.83	6.03	7.85
October	9.76	8.32	10.50	—	9.91	9.18	6.69	9.06
November	10.02	9.32	8.00	—	7.29	8.88	6.87	8.40
December	8.84	10.66	10.37	—	9.00	14.69	10.95	10.75
Annual average	9.67	9.04	9.81	8.74	8.42	8.74	7.80	8.89

where ρ is density of air. Wind power density of a site based on Weibull probability density function can be expressed as follows:

$$\frac{P}{A}=\int_0^\infty P(V)f(V)\,\mathrm{d}V=\frac{1}{2}\rho c^3\Gamma\left(\frac{k+3}{k}\right). \tag{10}$$

Once wind power density of a site is given, the wind energy density for a desired duration can be calculated as

$$\frac{E}{A}=\frac{1}{2}\rho c^3\Gamma\left(\frac{k+3}{k}\right)T, \tag{11}$$

where T is the time period. This value equals to 720 h for monthly duration.

Table 4
Monthly variation of Weibull parameters (k and c) for Aydıncık station between years 1994 and 2002

Month	Year						
	1994	1996	1997	1998	2000	2001	2002
	k (–)						
January	1.55	2.20	1.78	1.29	2.04	1.63	1.50
February	1.62	1.88	1.77	1.54	1.82	1.61	1.70
March	1.82	1.95	1.53	1.68	2.51	1.70	1.90
April	1.74	1.72	1.62	2.35	1.84	1.48	1.88
May	1.55	1.84	2.31	1.73	1.62	1.62	2.54
June	1.67	1.94	—	2.03	1.84	2.21	2.64
July	3.27	1.76	—	—	2.25	2.37	2.27
August	2.52	2.39	—	—	2.74	2.80	2.05
September	2.07	1.58	2.22	—	2.03	2.15	2.09
October	1.66	1.98	1.52	—	1.87	2.54	1.76
November	1.47	1.41	1.81	—	1.58	1.78	1.67
December	1.47	2.70	1.50	—	1.62	1.99	1.84
Annual average	1.69	1.75	1.65	1.60	1.81	1.69	1.77
	c (m/s)						
January	11.76	13.16	11.27	7.64	10.27	10.96	10.09
February	11.14	13.34	11.68	9.60	10.63	10.14	8.06
March	11.55	12.24	11.58	12.50	11.94	9.91	10.92
April	9.69	6.89	9.25	10.95	5.55	8.35	8.62
May	6.80	8.32	13.08	8.91	7.68	7.14	8.44
June	8.25	9.10	—	7.84	9.08	7.55	8.42
July	12.46	10.19	—	—	7.83	8.14	7.37
August	9.24	9.74	—	—	10.83	10.30	8.58
September	9.33	8.12	11.18	—	9.90	7.71	6.81
October	10.92	9.39	11.66	—	11.16	10.35	7.51
November	11.07	10.24	8.99	—	8.12	9.98	7.70
December	9.77	11.99	11.49	—	10.05	16.57	12.32
Annual average	10.13	10.15	10.97	9.75	9.47	9.79	8.76

Table 5
Monthly wind characteristics at four stations in Gökçeada Island

	January	February	March	April	May	June	July	August	September	October	November	December	Annual average
Aydincik													
k (–)	1.71	1.7	1.87	1.8	1.89	2.06	2.38	2.5	2.02	1.89	1.62	1.85	1.94
c (m/s)	10.74	10.65	11.52	8.47	8.62	8.37	9.2	9.74	8.84	10.16	9.35	12.03	9.81
V (m/s)	9.62	9.51	10.26	7.56	7.69	7.44	8.18	8.65	7.85	9.06	8.4	10.75	8.89
V_{mp} (m/s)	6.42	6.32	7.65	5.40	5.79	6.06	7.32	7.94	6.30	6.82	5.17	7.90	6.75
$V_{Max,E}$ (m/s)	16.89	16.83	17.00	12.83	12.63	11.63	11.89	12.32	12.43	14.89	15.36	17.88	14.13
P/A (W/m^2)	1225	1204	1343	560	556	463	544	624	557	910	877	1550	868
Ugurlu													
k (–)	1.36	1.55	1.45	1.27	1.46	1.56	2.28	3.93	1.49	1.44	2.1	1.51	1.34
c (m/s)	7.8	8.6	7.4	8.4	9.7	12.9	19.6	13.3	6.3	6.2	10.4	9.1	9.1
V (m/s)	7.2	7.8	6.7	7.8	8.8	11.6	17.3	12	5.7	5.7	9.2	8.2	8.3
V_{mp} (m/s)	2.94	4.41	3.30	2.48	4.40	6.69	15.22	12.34	2.99	2.72	7.64	4.43	3.27
$V_{Max,E}$ (m/s)	15.17	14.68	13.45	17.69	17.52	21.89	25.84	14.77	11.15	11.35	14.30	15.91	17.99
P/A (W/m^2)	713	742	529	1042	1168	2458	5404	1330	314	325	864	913	1155
NWS													
k (–)	1.42	1.82	1.9	2.4	1.81	1.84	2.16	2.39	1.5	1.33	2.62	1.86	1.68
c (m/s)	8.7	9.8	8.3	7.4	5	5.2	6.9	8.4	6.1	5.8	10.3	7	7.4
V (m/s)	7.9	8.7	7.4	6.6	4.4	4.6	6.1	7.4	5.5	5.4	9.2	6.3	6.6
V_{mp} (m/s)	3.69	6.32	5.60	5.91	3.21	3.40	5.17	6.70	2.93	2.03	8.57	4.62	4.32
$V_{Max,E}$ (m/s)	16.16	14.73	12.12	9.53	7.54	7.76	9.35	10.83	10.73	11.56	12.79	10.36	11.8
P/A (W/m^2)	895	843	494	287	112	123	250	409	272	313	723	309	415
Cinaralti													
k (–)	—	—	—	—	1.33	1.6	1.67	3.28	1.38	1.23	2.16	1.86	1.3
c (m/s)	—	—	—	—	14.9	12.8	15.1	10.9	5.9	6.7	12	7.8	10.4
V (m/s)	—	—	—	—	13.7	11.5	13.5	9.8	5.4	6.3	10.6	7	9.7
V_{mp} (m/s)	—	—	—	—	5.22	6.93	8.74	9.76	2.32	1.71	9.00	5.15	3.37
$V_{Max,E}$ (m/s)	—	—	—	—	29.71	21.25	24.20	12.60	11.29	14.69	16.25	11.55	21.29
P/A (W/m^2)					5150	2300	3518	773	303	572	1360	428	

3. Wind data

Gökçeada is an island located on the northwest of Turkey in the Aegean Sea. Maximum height of the island is about 700 m above the sea level. The study covers both the urban and rural areas of Gökçeada Island.

The wind data used in this present study consist of wind speed values recorded at four stations which are located in different parts of the island as shown in Fig. 1 with 10 min interval during the day, using methods recommended by the World Meteorological Organization [14].

The periods of observation with some additional information about the stations are presented in Table 1.

Wind data measurements were made at an elevation of 10 and 30 m above the ground level. Components used in measurement can be seen in Table 2.

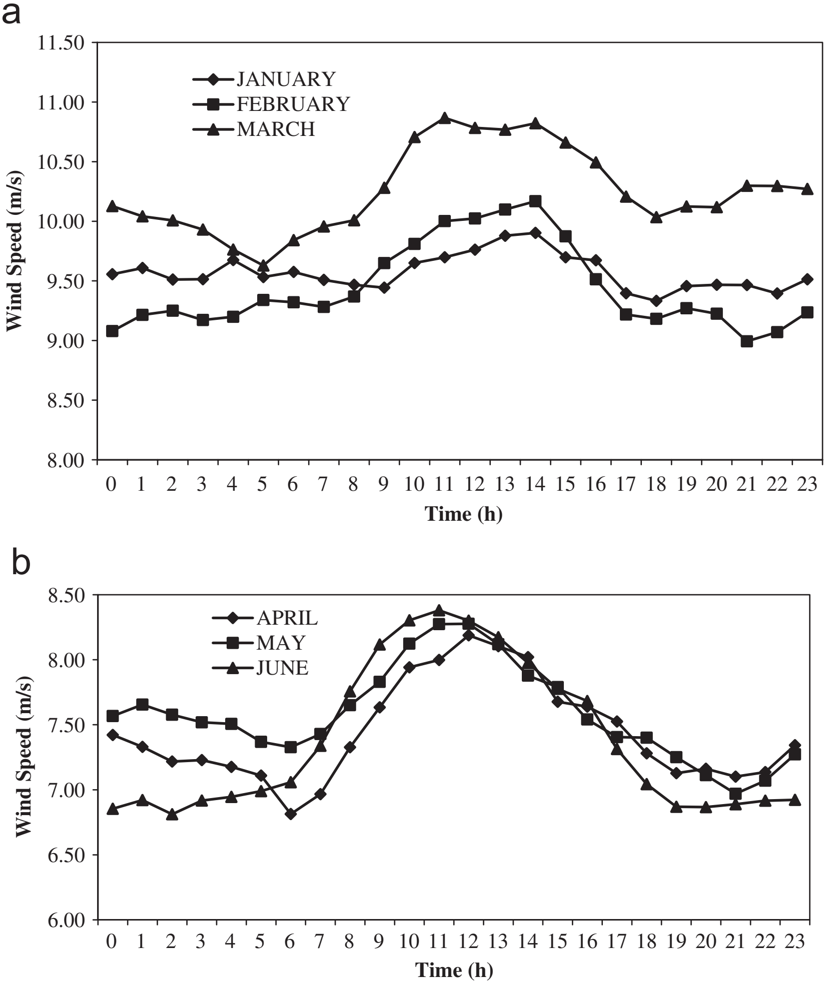

Fig. 2. Hourly average wind speeds in Aydıncık: (a) January–March, (b) April–June.

Wind speed data were extrapolated by using the following power-law formula [15]:

$$\frac{V(z)}{V(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha}, \tag{12}$$

where $V(z)$ is wind speed estimated at desired height z, $V(z_r)$ is wind speed at boundary layer height z_r and α is the power-law index. The values of z_r and α for each station were also obtained using the data measured at 10 and 30 m at each station.

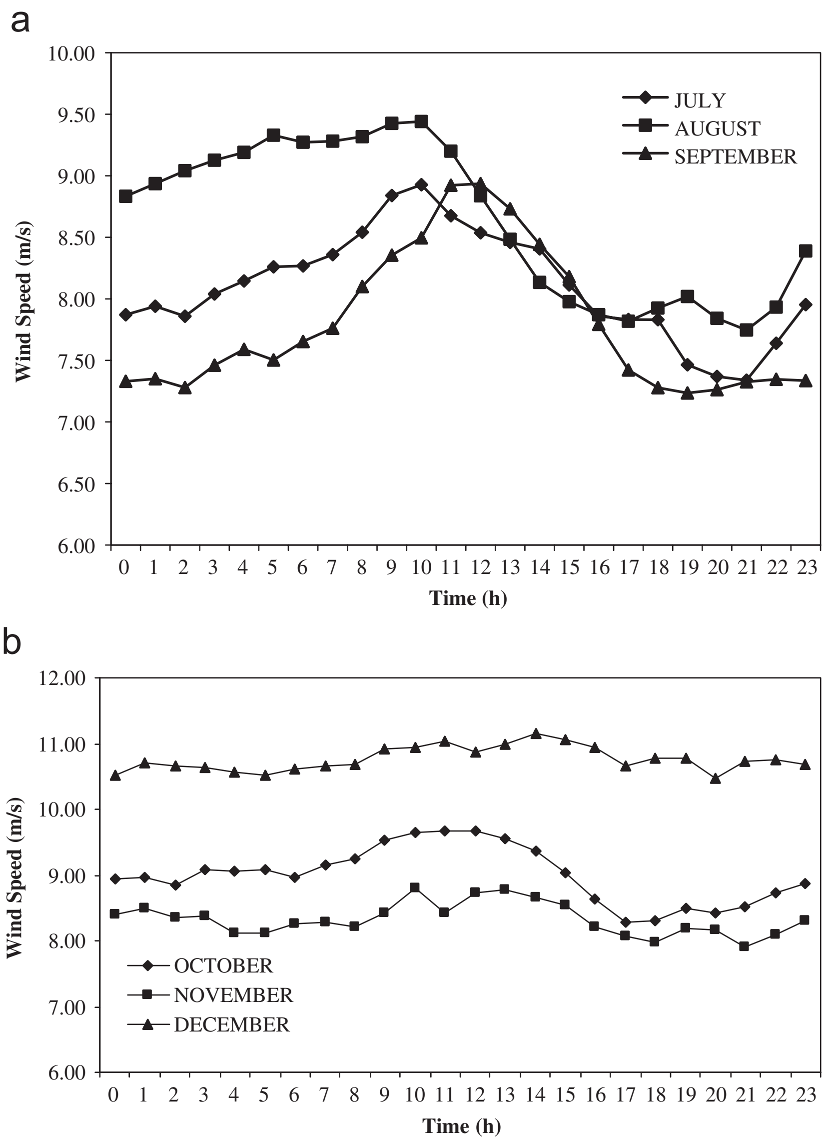

Fig. 3. Hourly average wind speeds in Aydıncık: (a) July–September, (b) October–December.

An evaluation procedure for estimating wind resource across Gökçeada Island is carried out. The first stage is to analyze the monthly wind speed distributions for the entire island. The yearly wind speed distributions as well as wind power density are further investigated to provide more detailed information of wind resources.

4. Monthly wind speed distributions

The analyses of the time series have been performed by grouping the hourly data month by month at each station. The choice to subdivide the year into monthly periods is due to the fact that calculations are performed on a monthly basis and that the wind has a relatively homogenous behavior within a month. The monthly average wind speed variation over a long-term data during the period 1994–2002 at the Gökçeada Aydıncık station is given in Table 3. The highest monthly average wind speed 14.49 m/s was observed in December 2001, but the annual average value of wind speed is over 7.8 m/s.

Weibull parameters of Aydıncık and the other three stations in Gökçeada are given on monthly basis in Tables 4 and 5, respectively. Although shape factor has greater values in summer time, c scale factor has its maximum values in winter for Aydıncık. Çınaraltı and Uğurlu stations have their maximum shape factor values in August, when NWS has it in November. Maximum scale factors for Uğurlu, NWS and Çınaraltı are in July, November and again July, respectively.

In Fig. 2a hourly average wind speeds in Aydıncık are given for January–March time period. March has wind speeds greater than 9.5 m/s during day time. In Fig. 2b hourly averages for 3 month are similar and in the range of 7.5–8.5 m/s. In Fig. 3a August has a maximum of 9.5 m/s wind speed at about 10 a.m.

In Fig. 3b December has almost homogenous hourly distribution for the day which is almost 11 m/s.

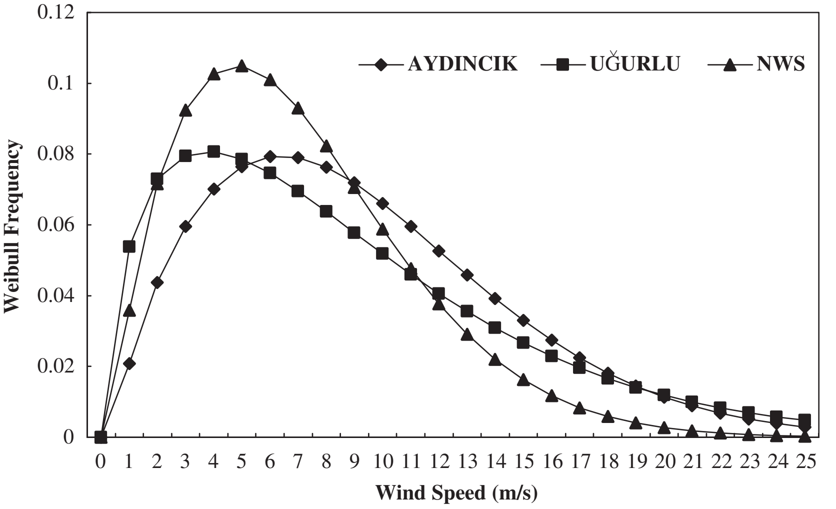

Fig. 4. Aydıncık, Uğurlu and National Weather stations annual Weibull distribution.

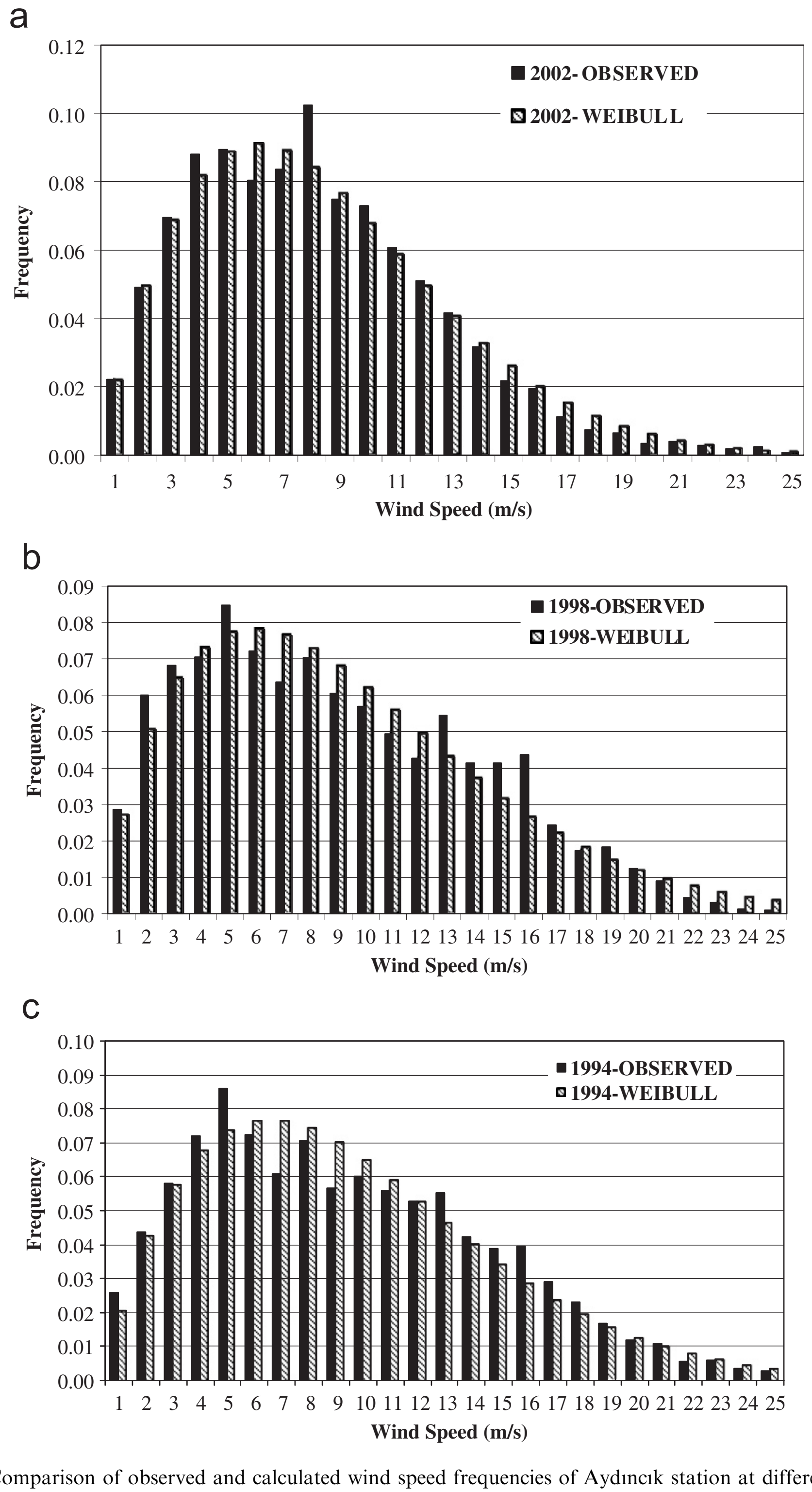

Fig. 5. Comparison of observed and calculated wind speed frequencies of Aydıncık station at different years.

For the whole year, December has an outstanding wind speed potential. It can be clearly seen that winter is the best time for the wind speed distributions in Aydıncık. March also has wind speed potential as much as the winter months.

5. Annual wind speed distributions

Fig. 4 shows the annual Weibull distribution of Aydıncık station, Uğurlu and NWS station. Weibull frequency reaches at top point at about 7 m/s with a value of about 0.08. After that point the curve drops steadily. For 14 m/s, the curve gives a frequency of about 0.04; it drops 0.02 at 18 m/s wind speed. In Uğurlu station at 4 m/s wind speed, Weibull frequency reaches 0.08 and drops steadily from this point on. Weibull frequencies are found as 0.03 at 14 m/s wind speed and as 0.02 at 18 m/s wind speed for Uğurlu station. Maximum Weibull frequency of 0.1 can be seen on the curve for 5 m/s wind speed in NWS station. Same trend of dropping frequencies occurs again after the maximum point 0.03 and 0.02 frequencies are found for 14 and 18 m/s wind speeds, respectively.

Uğurlu and Aydıncık have high frequency values for high wind speeds. So, the annual average wind speeds become higher in these regions.

Fig. 5(a–c) shows the annual variation of observed and Weibull wind speed frequencies for 2002, 1998 and 1994 years in Aydıncık, respectively. Maximum percentage error between Weibull wind speed frequencies and observed frequencies occurs at 16 m/s wind speed with a value of 25% (Fig. 5b).

Fig. 6 shows the average annual variation of observed and Weibull wind speed frequencies in Aydıncık. It can be clearly seen that Weibull function fits the observed distribution reasonably well in the relevant wind range.

For a wind turbine with cut-in speed of 3 m/s, rated speed of 14 m/s and cut-off speed of 25 m/s, we can make an estimate of loading conditions during the year. The turbine would work 20% of the time of the year at rated load, 72% of the time at partial load and 7% of

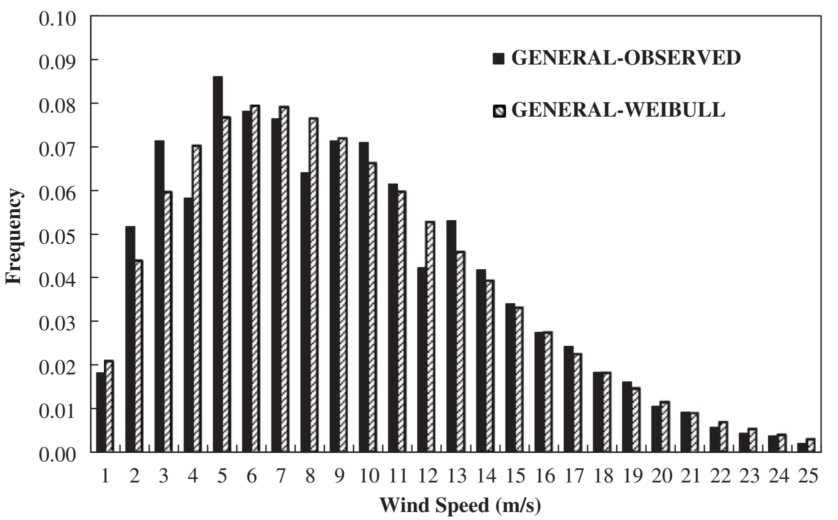

Fig. 6. Comparison of observed and calculated wind speed frequencies of Aydıncık station.

the time would be at a standstill. 1% of the time of the year the turbine would face-off wind speeds higher than 25 m/s.

6. Conclusion

The monthly and yearly wind speed distribution and wind power density in Gökçeada Island is evaluated to provide the basic information of wind source, which indicates that there exists a wind resource in the area. To assess the wind potential of Gökçeada Island, time series of wind speed data that has been collected at 10 and 30 m of height above the ground were extrapolated to 50 m which had been chosen as the wind turbine hub height, using power law. New wind data values of Aydıncık site and the other three sites had been used to find the wind speed distribution curves. It may be concluded that the Weibull distribution presented here indicates a good agreement with the data obtained from actual measurements. Stations have different periods of high wind speed frequency distributions. December and March are the 2 months that the average wind speeds are the highest of all year in Aydıncık. Uğurlu region has high frequencies of high wind speeds in summer. This study has explicitly demonstrated the presence of high wind speeds and power in Gökç eada, as well as in the northern-western part of Turkey.

References

[1] Stevens MJM, Smulders PT. The estimation of parameters of the Weibull wind speed distribution for wind energy utilization purposes. Wind Eng 1979;3:132–45.
[2] Justus CG, Hargraves WR, Yalcin A. Nation wide assessment of potential output from wind powered generators. J Appl Meteorol 1976;25:673–8.
[3] Ackermann T, Söder L. An overview of wind energy-status. Renew Sust Energy Rev 2002;6:67–128.
[4] Kaygusuz K. The role of renewables in future energy directions of Turkey. Energy Sources 2004;26:1131–40.
[5] Rohatgi JS, de Meiros ALR, Cavalcanti RA. Statistical testing of Weibull and other frequency distributions of wind speed variations for different sites. In: EWEC'89, Proceedings of European wind energy conference and exhibition. Brazil: Peter Peregrino Ltd; 1998. p. 880–3.
[6] Rehman S, Halawani TO, Husain T. Weibull parameters for wind speed distribution in Saudi Arabia. Sol Energy 1994;53:473–9.
[7] Gupta BK. Weibull parameters for annual and monthly wind speed distributions for five locations in India. Sol Energy 1986;37:469–71.
[8] Rosen K, Buskirk Van R, Garbesi K. Wind energy potential of coastal Eritrea: an analysis of sparse wind data. Sol Energy 1999;66:201–13.
[9] Garcia A, Torres JL, Prieto L, DeFrancisco A. Fitting wind speed distributions: a case study. Sol Energy 1998;62:139–44.
[10] Patel MR. Wind and solar power systems. Florida, USA: CRC Press; 1999.
[11] Chang TJ, Wu YT, Hsu HY, Chu CR, Liao CM. Assessment of wind characteristics and wind turbine characteristics in Taiwan. Renew Energy 2003;28:851–71.
[12] Balouktsis A, Chassapis D, Karapantsios TD. A nomogram method for estimating the energy produced by wind turbine generators. Sol Energy 2002;72:251–9.
[13] Jamil M, Parsa S, Majidi M. Wind power statistics and evaluation of wind energy density. Renew Energy 1995;6:623–8.
[14] World Meteorological Organization. Meteorological aspects of wind as an energy source. Technical Note 175; 1981.
[15] Manwell JF, McGowan JG, Rogers AL. Wind energy explained. New York: Wiley; 2002.